CHAPTER IV

RELATIONSHIP BETWEEN CROP TEMPERATURE AND THE PHYSIOLOGICAL AND PHENOLOGICAL DEVELOPMENT OF DIFFERENTIALLLY IRRIGATED CORN

B. R. Gardner, B. L. Blad, R. E. Maurer, D. G. Watts

ABSTRACT

Quantitative data relating crop temperature under different water stress conditions to the phenological and physiological development of corn over a growing season are lacking. This study was motivated by the need to obtain quantitative information which can be beneficially utilized by those who are involved in predicting crop yields and assist those who assess the economic impact of drought on crop production.

Infrared canopy temperatures and physiological and phenological measurements were made in differentially irrigated corn (_Zea mays_ L.) throughout the 1978 growing season. Irrigation treatments were designed to evaluate the effects of moisture stress on these measurements. The soil type in the experiment area is Valentine fine sand (Typic Ustipsamment).

The effect of moisture stress on vegetative growth was demonstrated by an average height difference of 50 cm between fully irrigated and non-irrigated plants.

There was a tendency for plants which had been subjected to moisture stress during the grainfilling stage to mature faster than plants fully irrigated during that period.

Yield reductions were greatest when stress occurred during the pollination or grain-filling periods. Canopy temperature increases between the onset of tasseling and the end of grain-fill

were related to reduced yields.

Five crop temperature indices were tested for their relationship to phenological stage of growth. Three were highly correlated, one had a low correlation and one was not correlated with phenological development.

INTRODUCTION

Hsiao (1973) has summarized the observed plant responses to water stress, which include reductions in the transpiration rate CO_2 assimilation rate, leaf cell size, plant-water potential, growth rate and stomatal aperature. Glover (1959) concluded that evaluation of stomatal response to moisture stress requires a knowledge of the moisture history of the plant. Clark (1973) concluded that the status of water in plants represents an integration of the atmospheric demand, soil-water potential, rooting density and distribution, and other plant characteristics. Thus, for a true measurement of plant moisture deficit, measurements should be made on the plant instead of the soil or atmosphere.

The effect of moisture stress on vegetative growth and grain yields in corn depends on the degree of stress and on the stage of growth at which stress occurs (Somerhalder, 1962; Sionit and Kramer, 1977). Denmead and Shaw (1960) observed that stress in corn during silking was more harmful to grain yields than stress during any other growth stage.

Reicosky et al. (1975) theorized that a physiological change occurs in corn during pollination which makes the interpretation of leaf water potential measurements after that stage difficult, whereas leaf water potential measurements during the vegetative

period were related to stress.

Ehrler (1973) stated that long-term leaf temperature measurements are an indirect indication of stomatal behavior. Ehrler et al. (1978) demonstrated that canopy temperature in wheat increased as plant water potential decreased. Differences in canopy temperatures between stressed and non-stressed wheat plants were shown to be a reliable indicator of plant moisture stress.

Quantitative data relating crop temperature under various water stress conditions to the phenological and physiological development of crops over a complete growing season are sparse. The only seasonal crop temperature studies reported thus far are those of Idso et al. (1977) and Jackson et al. (1977) with durum wheat. They showed that an accumulation of crop temperatures during the period between head emergence and the cessation of head growth were related to final grain yields.

The lack of quantitative information in relating canopy temperature to the development of corn (Zea mays L.) motivated the study reported here. The specific objectives of the research were: (1) to evaluate the effectiveness of five crop temperature indices in estimating phenological growth stage and (2) to use information on canopy temperature to estimate reduction in grain yield due to moisture stress.

MATERIALS AND METHODS

Experimental Site

This study was conducted at the University of Nebraska Sandhills Agricultural Laboratory, located near Tryon, Nebraska

(41° 37' N; 100° 50' W; 975 m above sea level). The combination of low rainfall during the growing season, sandy soil (Valentine fine sand - Typic Ustipsamment) and high evaporative demand makes it possible to study the effects of moisture stress at this location without the use of rainout shelters.

Measurements were conducted on nine plots of corn (*Zea mays* L., cv. Pioneer 3780), each of which measured 27 meters (N to S) by 9 meters (E to W). Each plot contained 24 rows, each 76 cm wide. Along the east and west border of each plot was a solid set sprinkler irrigation system similar in design to that of Hanks et al. (1976). The system which permits the application of water in a gradient across a plot is described in detail in Chapter II.

Irrigation Treatments

Seven different irrigation treatments were employed in this study (Table 1). Each treatment was replicated twice. The full irrigation treatment (I) consisted of restoring 100% of the water used in evapotranspiration to all rows in a plot. The amount of water evapotranspired was determined by measuring soil moisture depletion with a neutron probe. The gradient treatment (G) consisted of applying full irrigation to row 1 of a plot and applying progressively less moisture to each succeeding row, until rows 22 through 24 received essentially no irrigation.

Irrigations were timed to coincide with each of three growth periods: vegetative growth, pollination and grain-filling. The vegetative stage treatments began on June 10, the pollination stage treatments on July 18, and the grain-filling stage treatments on August 12.

Table 1. The seven irrigation treatments used for the study. I means that all rows in a plot received a full irrigation during that growth period. G means that an irrigation gradient was established so that one side of the plots received 100% of its water needs, while no replacement of water was made to the opposite side.

Treatment	Growth Stage		
	Vegetative	Pollination	Grain Filling
1	G	I	I
2	I	G	I
3	I	I	G
4	G	I	G
5	I	G	G
6	G	G	G
7	G	G	I

Soil Plant and Air Measurements

Phenological measurements using the system of Hanway (1966) were made for all moisture treatments at least once each week throughout the growing season. Each plant height and phenological stage observation was made on at least 10 individual plant samples.

Canopy temperatures were measured with an infrared thermometer (IRT) each day between 1200 and 1330 solar time on rows 2, 6, 10, 14, 18 and 22 of each plot. Readings began on June 1 and continued throughout the growing season, except for a few days when measurement was not possible. Two infrared thermometers were used. A Telatemp model 44 was used between June 13 and July 17. A Barnes model PRT5 was used the remainder of the season. True canopy temperature was calculated from the following expression:

$$T_C = \frac{(\sigma T_{IR}^4 - (1 - \varepsilon_C)B^*)^{\frac{1}{4}}}{\varepsilon_C \sigma}$$

where T_C is the true canopy temperature (°K), T_{IR} is the apparent canopy temperature sensed by the IR thermometer (°K), σ is the Stefan-Boltzman constant, ε_c is the crop emissivity and B^* is the incoming longwave radiation. Estimates of B^* were obtained at least twice during mid-day, using the aluminum plate apparatus described by Blad and Rosenberg (1976). The aluminum plate was repainted weekly.

Three techniques for measuring infrared canopy temperatures of a particular row were employed. The direct method consisted of placing the IRT next to the upper leaves of a plant. The average of four direct readings was used to represent the canopy

temperature of a given row. The direct method was especially useful during the early part of the growing season when the plants were so small that, if viewed from a distance, bare soil influenced the IRT temperatures so strongly that temperature differences between plants were entirely masked. The direct method was used from June 14 to June 28. Prior to June 14, the plants were so small that they did not entirely cover the area viewed by the IRT. Thermocouple temperatures of sunlit leaves were used as an estimate of canopy temperatures prior to June 14.

The method used from June 29 through July 7 consisted of standing directly in line with a row and viewing an area 5 meters away. Though crop cover was not complete during this period, and differences in crop cover existed between irrigated and nonirrigated rows, the small spot size (less than 25 cm in diameter) of the IRT allowed it to view, essentially, only the canopy.

The third technique, used from July 8 to the end of the study, consisted of viewing the canopy temperature from atop a 3 meter aluminum ladder which was positioned in line with row 14. The maximum width of the IRT spot size was 95 cm; the maximum length was 200 cm. Thus, these IRT measurements integrated the temperature of several plants, primarily those along a single row.

Detailed measurements of leaf temperature profiles were made in one plot. Leaf temperatures were measured throughout the season at 3 different levels (bottom, middle and top) within this plot in rows 2, 6, 10, 14, 18 and 22.

Leaf temperatures at a given level were measured with

evanohm-constantan thermocouples using the method of Steinmetz (1977). Beginning on June 23, leaf temperatures were recorded at least hourly with a Campbell CR5 data logging system. Prior to June 23, leaf temperatures were measured with a hand-held thermocouple meter.

Crop Temperature Indices for Estimating Crop Growth Stage

Five crop temperature indices were evaluated to determine how well they would estimate crop growth stage. These are given in Table 2. Index 1 is the sum of the mid-day canopy temperature. Index 2 is commonly reported in the literature to indicate whether or not a crop is experiencing moisture stress. Jackson et al. (1977) assumed that a crop experiences moisture stress only when index 2 is positive. Index 3 assumes that crop moisture stress occurs whenever positive values are observed; it also requires that a nonstressed area be available for comparing canopy temperatures. Index 4 is similar to a moisture stress index reported by Idso et al. (1977). Index 5 is analogous to the growing degree day. All indices were calculated daily throughout the growing season.

RESULTS AND DISCUSSION

Plant Height

Plants in plots which were fully irrigated during the vegetative period showed little difference in height across the plot. Those in plots which received a differential irrigation treatment showed a substantial reduction in height from the fully-irrigated to the non-irrigated side of the plot. The greatest difference in average plant height among the fully

Table 2. The five crop temperature indices used to estimate crop growth stage. Each index was summed on a daily basis. T_x is the mid-day canopy temperature of row 2, 6, 10, 14, 18 or 22 in a given plot. T_a is the mid-day air temperature 3 meters above the soil surface. T_{min} is the minimum leaf temperature.

$$\text{Index 1} = \Sigma\, T_x$$

$$\text{Index 2} = \Sigma(T_x - T_a)$$

$$\text{Index 3} = \Sigma(T_x - T_2)$$

$$\text{Index 4} = \Sigma(T_x - T_{min})$$

$$\text{Index 5} = \Sigma\left(\frac{T_x + T_{min}}{2} - 10\right)$$

irrigated plants was 15.9 cm while differences between the fully irrigated and non-irrigated plants on the gradient plots were as great as 50.1 cm.

Moisture and temperature stress resulted in measurable differences in plant height between June 10, when the first gradient treatment was applied, and June 19. There was no significant difference in height between irrigated and non-irrigated plants between June 10 and June 13. June 14 and 15 were hot, cloudless days and produced a visible gradient in wilting across the plot. Plants in the fully irrigated rows were slightly wilted while those in the non-irrigated rows were severely wilted. *T, the difference in mid-day temperature between stressed and non-stressed sunlit leaves was 3.0 C on the 14th and 3.6 C on the 15th. On June 16, irrigated plants were 3 cm taller than were non-irrigated plants. By June 19, well-watered plants were 8-14 cm taller than the non-irrigated ones.

Phenological Development

Phenological differences were not observed among the various moisture treatments until after stage 8, when plants were approaching maturity. During the latter stages of the grain-filling period there was a trend for water stressed plants to mature faster than unstressed plants. By September 13, the stressed plants were 0.5 to 0.7 of a growth stage ahead of the well watered ones. Maturity differences are expected since physiological maturity cannot occur until the plants have dried sufficiently. Hence, moisture stressed plants can be expected to dry and mature slightly sooner than do non-stressed plants.

Crop temperature indices 1, 4 and 5 were highly correlated ($R^2 = 0.98$) with phenological stage of development (Fig. 1). Any one of these indices may thus be used to estimate crop growth stage. R^2 was only 0.57 for index 3. This is explained as follows: temperature differences between stressed and non-stressed areas occur only when atmospheric demand for water is sufficiently great. When atmospheric demand is low, no positive values accrue. The lack of correlation ($R^2 = 0.02$) for index 2 is due to the fact that differences between canopy temperature and air temperature fluctuate in both sign and magnitude according to atmospheric demand. Consequently, index 2 may be positive or negative on a given day. Index 2 is not suitable for estimating crop development. Index 1 is the most convenient index for estimating growth stage, since only one daily measurement is required instead of the two daily measurements required by indices 4 and 5. But index 1 (and index 4) will not be reliable in areas where the temperature falls below some base value (10 C in corn), since positive values will accumulate even though crop development has ceased. For such conditions index 5 is more suitable.

Crop growth stage, as predicted by index 1, was compared with weekly phenological measurements from plots which were not included in development of the correlations in Fig. 1. The agreement between predicted and observed stage of growth was good ($R^2 = 0.98$) (Fig. 2).

These results suggest that crop temperature data obtained with infrared thermometers or from airborne or satellite scanners can be used to predict phenological growth stages. This may be particularly valuable when air temperature data near the surface

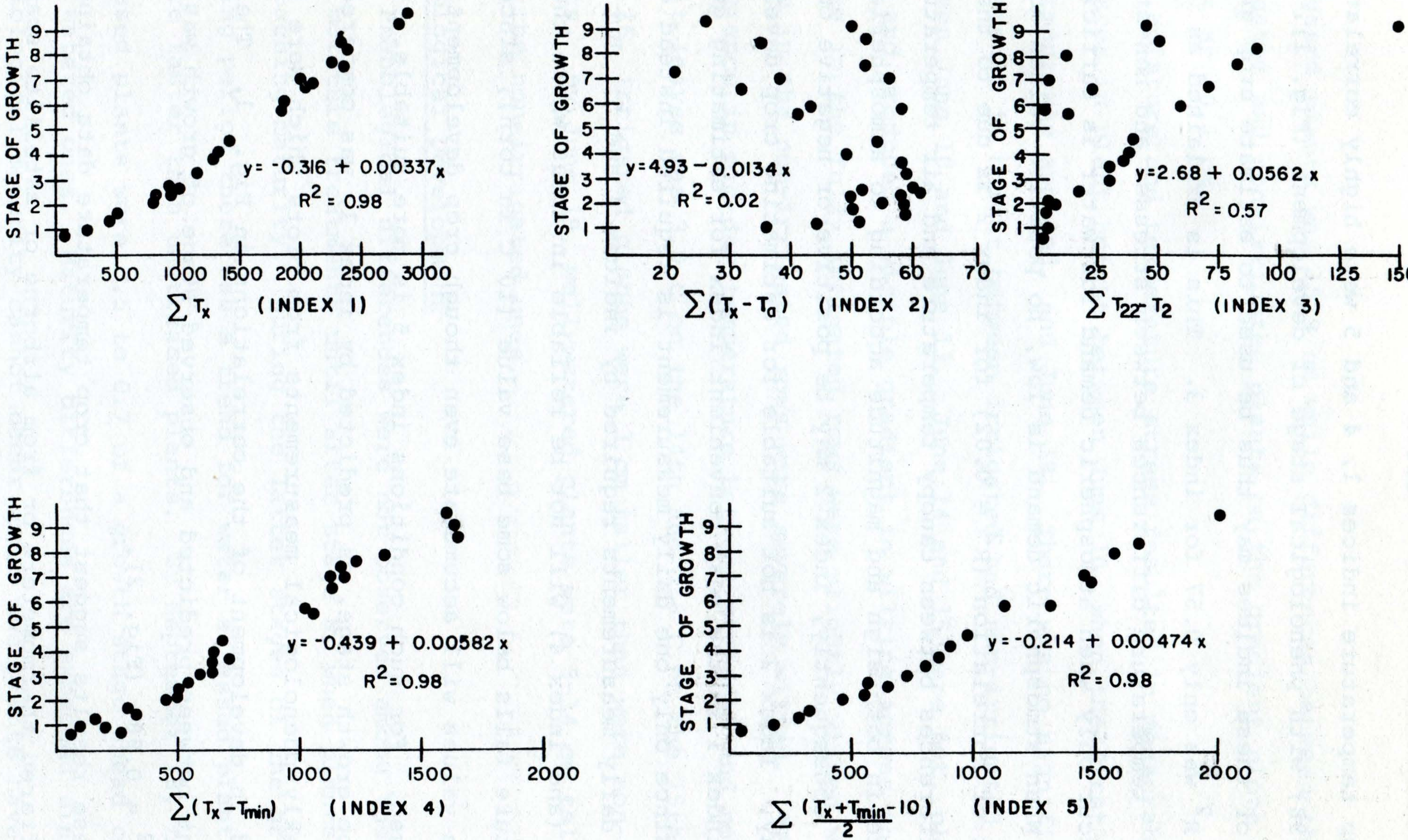

Fig. 1. Relationship between crop growth stage and the five crop temperature indices defined in Table 2.

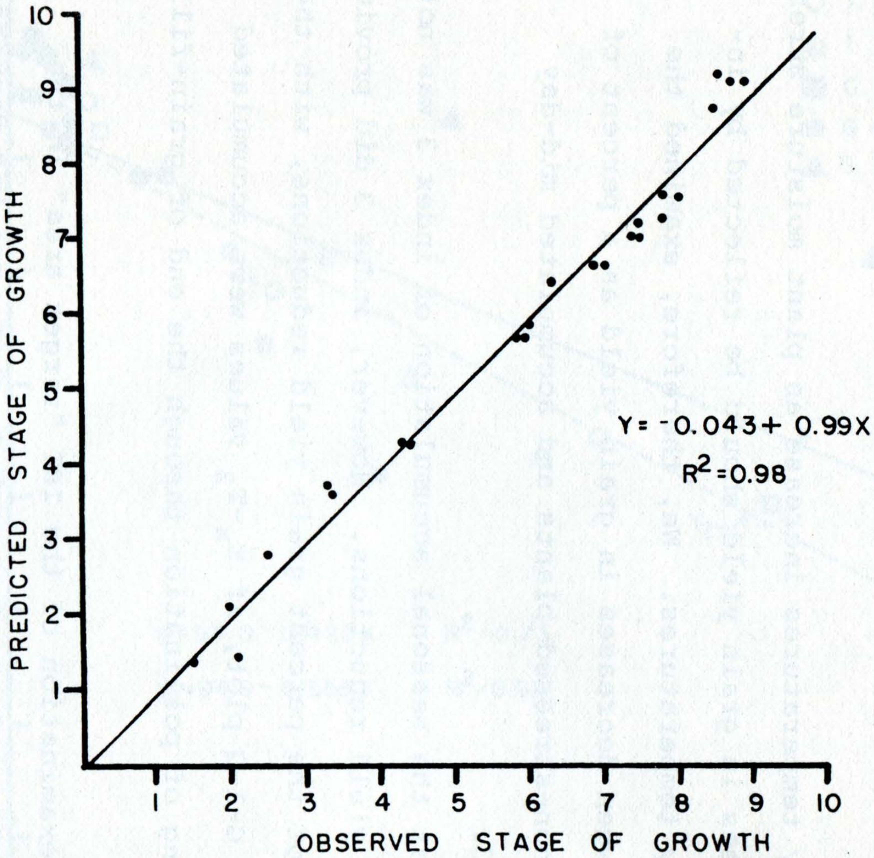

Fig. 2. Observed stage of growth versus that predicted by index 1. Predicted stage of growth = -0.316 + 0.00337x, where x equals the summation of mid-day canopy temperature (crop index 1).

is unavailable to compute growing degree days.

Grain Yields

Stress during vegetative growth only (G-I-I) had the least damaging effects on yield, while stress during both the grain-filling and pollination stages (I-G-G and G-G-G) had the greatest limiting effect on yield. Yields were moderately reduced when stress was avoided during either pollination or grain-filling (I-I-G; I-G-I; G-I-G; and G-G-I). The average grain yield on the fully irrigated rows of all plots was 123 ± 4 q/ha (196 ± 6 bu/acre).

Since canopy temperatures increase as plant moisture stress develops, decreases in grain yield should be reflected by increases in canopy temperatures. We, therefore, examined the relationship between decreases in grain yield as a percent of the yield among non-stressed plants and accumulated mid-day values of index 3.

We found that the seasonal accumulation of index 3 was not related to grain yield reductions. However, index 3 did provide a good estimate of the percent grain yield reductions, with the exception of the G-I-G plot, if T_x-T_2 values were accumulated from the beginning of pollination through the end of grain-filling (Fig. 3).

A detailed examination of the IRT "target area" in the G-I-G plot revealed that plant growth in that area was depressed, probably because of a micro-nutrient deficiency (Gardner and Blad, 1980).

The depressed area in the G-I-G plot extended into only part of the yield sampling area. Therefore, the temperature in the

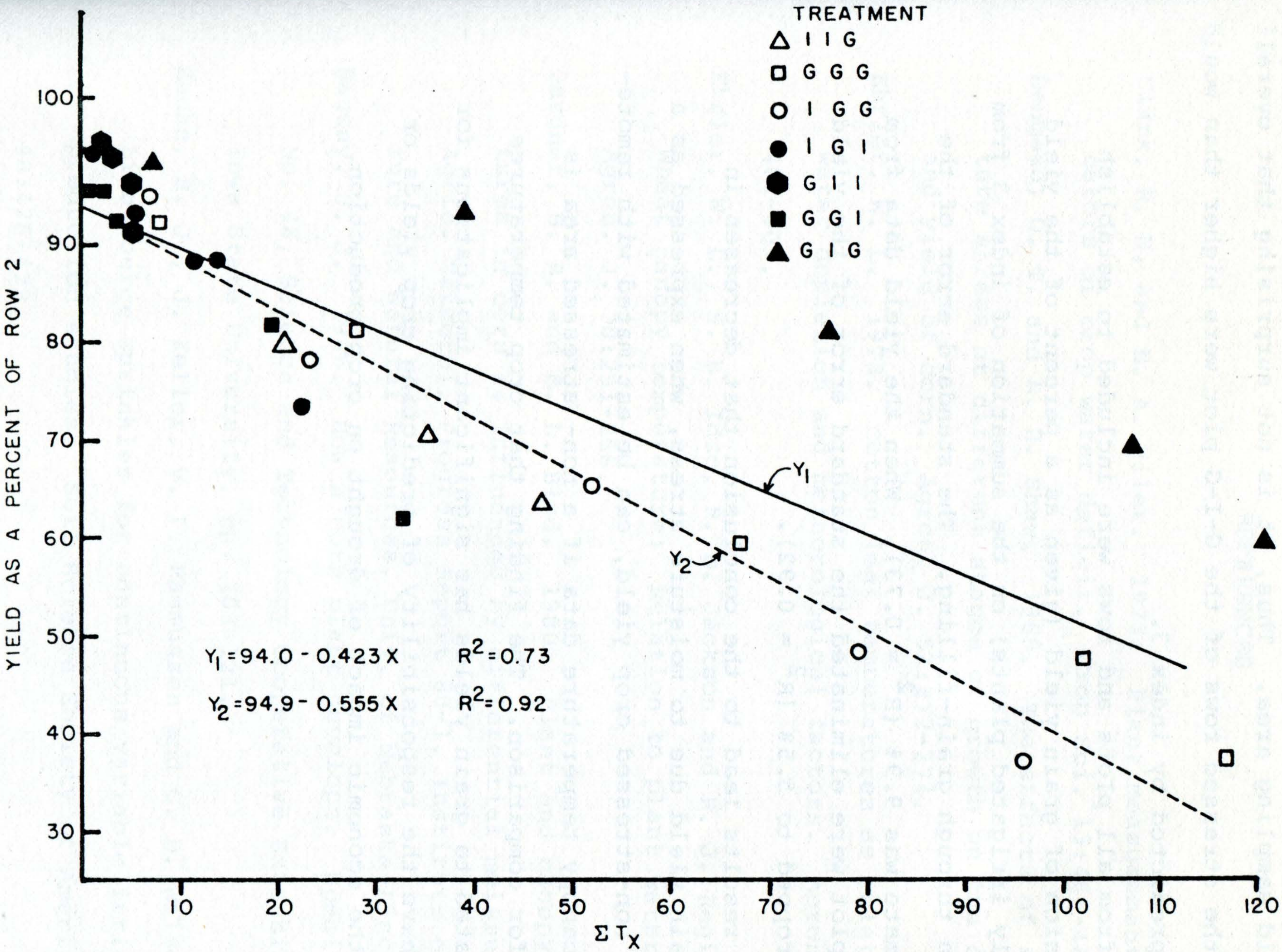

Fig. 3. Regression of grain yield (as a percent of the yield from fully irrigated plants) on the sum of index 3 from July 19 - September 13, 1978 (beginning of pollination to harvest). Y_1 includes the data from all plots. Y_2 excludes the data from the G-I-G plot.

"target area" for IRT measurements did not reflect plant performance in the yield sampling area. Thus, it is not surprising that overall yields on the stressed rows of the G-I-G plot were higher than would have been predicted by index 3.

Data from all plots and rows were included to establish the regression of grain yield (given as a percent of the yield of the fully irrigated plants) on the summation of index 3 from pollination through grain-filling. The standard error of the yield estimate was 9.9% ($R^2 = 0.73$). When the yield data from the G-I-G plot were eliminated the standard error of the yield estimate dropped to 5.5% ($R^2 = 0.92$).

These results lead to the conclusion that decreases in optimum grain yield due to moisture stress, when expressed as a percent of non-stressed crop yield, can be estimated with remotely sensed canopy temperature data if a non- stressed area is available for comparison. The finding that crop temperatures can be related to grain yields has significant implications for those who have the responsibility of predicting crop yields or assessing the economic impact of drought on crop production.

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